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Modeling crop water consumption and water productivity in the middle reaches of Heihe River Basin

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Abstract

Heihe River Basin is located in the arid inland area of northwest China and is facing serious water shortage problems. Since irrigation is the largest water consumer in the middle reaches of the Basin, it is crucial to study the crop yields and water consumption in order to improve the agricultural water productivity and to support sustainable economic development in this region. Based on field experiments in 2012 on typical crops, AquaCrop model was calibrated for seed maize, field maize and spring wheat; the models were validated using monitored data in 2013. Then considering the spatial distribution of soil types, groundwater depth, agricultural management and cropping patterns, ArcGIS was applied for the pre/post processing of

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the AquaCrop to quantify the spatial distribution of water consumption and water use efficiency (WUE) in a typical irrigation district and the whole middle reaches. Results indicate that the AquaCrop model can reasonably simulate the canopy cover development, biomass accumulation and crops yield, as well as the evolution of soil moisture in this area. For example, the Nash-Sutcliffe efficiency index for seed maize canopy cover was at least 0.91 during calibration and 0.96 during validation. Spatial analysis of simulated water consumption showed that total water consumption decreased from east to west due to the nature of the crops and the area cultivated. WUE for all the crops was above unity, with the vegetables recording the highest in 2012 and 2013 of $2.74 \text{ kg}\cdot\text{m}^{-3}$ and $3.19 \text{ kg}\cdot\text{m}^{-3}$ respectively. The least WUE was recorded for spring wheat, i.e. $1.19 \text{ kg}\cdot\text{m}^{-3}$ and $1.67 \text{ kg}\cdot\text{m}^{-3}$ in 2012 and 2013 respectively. Further simulations under future possible climate change scenarios showed that WUE of seed maize and field maize might rise to some extent, while WUE for spring wheat might decrease by 0.39% in 2030 but increase by 14.63% in 2050 under climate change scenario SRES B2.

Key words: AquaCrop; Soil moisture; Crop water consumption; Crop yield; Crop water productivity; Heihe River Basin

1. Introduction

The middle reaches of Heihe River Basin, located in the arid region of northwest China, is facing serious water shortage problems due to the large-strong evaporation potential,

~~small~~ little precipitation, limited upstream water inflow, and the mandatory water discharge to downstream areas since 2000 (Ministry of Water Resources 2001). The continued development of the local economy requires even more water resources, while the evidence provided by the deteriorating natural vegetation in this region indicates that the available water resources was over-utilized (Chen et al. 2005). Water consumption in agriculture accounts for more than half of the total water abstraction (Xu and Cheng 2000), and currently considerable amounts of water diverted for irrigation are not effectively used for crop production (Smith 2000). Therefore quantification of the crop water consumption and the water productivity in this area is an essential step towards the development of more efficient systems for allocating of the limited water resources for the overall benefit of the local economy while preserving the integrity of the natural environment.

Evapotranspiration (ET) is the consumptive use of water for crop growth. Thus, water productivity evaluation requires an understanding of the relationship between crop growth and ET, for various types of crops. ET can be obtained by direct measuring or indirect calculation. Weighing lysimeters, eddy covariance systems and Bowen ratio systems are often-used tools for the direct, *in situ* measurement of ET (Wegehenkel and Gerke, 2013; Holland et al., 2013; Liu et al., 2013). However, because such measurements are expensive, time consuming and site specific, the indirect (or calculation) methods are often preferred. The indirect or calculation methods for ET (or evaporation) include the Penman model (Penman, 1948), Penman-Monteith (PM)

model (Monteith, 1965), or reference ET methods such as FAO56 Penman-Monteith (FAO-PM) method (Allen et al., 1998) and KSOM-based method (Adeloye et al., 2011).

Crop models were developed in the last few decades for understanding the relationship between dynamic crop growth indices and their main controlling factors (Bouman et al. 1996). There are mainly three types of crop growth models according to their key driving factors, i.e., carbon-driven models, radiation-driven models and water-driven models (Abedinpour et al. 2012). Carbon-driven models describe the crop growth based on carbon assimilation and one of the representative models is WOFOST (van Diepen et al. 1989). Radiation-driven models derive the crop biomass directly from the intercepted solar radiation through a single conversion coefficient, known as the radiation use efficiency (Monteith and Moss 1977). Examples are EPIC (Jones et al. 1991; Cabelguenne et al. 1999) and CERES model (Ritchie and Otter 1984). The latter is a model based on crop growth controlled by phenological development processes, and has been widely used to simulate the responses of yields and water use efficiencies of wheat and maize to climate change scenarios (Guo et al. 2010).

Water-driven models normally assume that crop growth rate is linearly proportional to transpiration through a constant of proportionality known as the water productivity (WP) parameter (Steduto and Albrizio 2005). They are particularly suitable for conditions such as those in northwest China where water is the key limiting factor ~~of~~for crop production. Compared with carbon-driven models and radiation-driven models,

79 water-driven models are the least complex and most parsimonious (Steduto et al. 2007;
80 Steduto et al. 2009). There are mainly two water-driven models in common use --
81 CropSyst (Stockle et al. 2003) and AquaCrop (Steduto et al. 2009). Of these, AquaCrop,
82 developed by the Food and Agricultural Organization (FAO) of the United Nations, has
83 seen the most use because of its simplicity and the fact that for most commonly grown
84 crops, further calibration is often not required (Vanuytrecht et al. 2014). It has been
85 widely used and applied successfully to different crops, like barley (Nazari et al. 2013),
86 wheat (Salemi et al. 2011; Lorite et al. 2013), maize (Kim and Kaluarachchi 2015),
87 cabbage (Kiptum K et al. 2013), seed cotton (Voloudakis et al. 2015) and some others
88 (Vanuytrecht et al. 2014; Paredes et al. 2015). For these reasons, AquaCrop was
89 adopted for the current study.

90 Most of the crop models including AquaCrop are point-scale models based on plot or
91 field experiments and are unable to consider spatial heterogeneity in such factors as
92 crop types, soil characteristics and irrigation practices and scheduling. However, unless
93 such point scale evaluations can be up-scaled to the much more useful regional scale,
94 the full impacts/benefits of this kind of analysis cannot be realized. Geographic
95 Information Systems (GIS) can be used to extend their applications to regional scale
96 through loose, close or embedded coupling (Ines et al. 2002; Mo et al. 2009; Fortes et al.
97 2005). For example, Lorite (2013) manipulated the AquaCrop input and project files in
98 a GIS platform and developed two tools (AquaData and AquaGIS) to manage the
99 programs, which not only saved operating time but also enabled the simulation of the

regional impacts of climate change on wheat yields in Andalusia, Spain. Jiang (2015) adopted a similar analysis to characterize water consumption and yield using SWAP-EPIC and ArcGIS for an irrigation district in China. In the current study, however, we have extended the work by Jiang (2015) to cover the entire middle reaches of Heihe River Basin, thereby providing for the first time useful information that will aid irrigation water management in this main agricultural region of northwest China.

The aim of this study therefore is to evaluate the spatial pattern of crop water consumption and water use efficiency (WUE) in the middle reaches of Heihe River Basin, a basin characterized by heterogeneous soil textures, various types of crops, and with limited water resources, using AquaCrop loosely coupled with ArcGIS for the pre/post processing. The objectives are to:

- (1) Evaluate the performance of AquaCrop for predicting local soil water balance and crop yield based on the field experiment data from 2012 to 2013;
- (2) Quantify the total water consumption and WUE, and their spatial distribution in the typical irrigation districts and in the ~~while~~-whole middle reaches of Heihe River Basin;
- (3) Predict the response of regional crop growth and water consumption under future possible climate change scenarios.

In the next Section, the methodology adopted for the study and the materials are described. ~~Next~~Then, the results and discussions are presented, after which follows the main conclusions of the study.

2. Materials and methods

Fig. 1 depicted the method for calculating the water consumption and WUE in the middle reaches of Heihe River Basin. The water consumption was analyzed in three scales, the spot scale with typical crops, the regional scale in a typical district (i.e., Yingke Irrigation District) and the large regional scale in the middle reaches of Heihe River Basin (including 17 main irrigation districts). Seed maize, field maize, spring wheat and vegetable were selected as the typical crops to be investigated because of their popularity in this area. The water consumption and yield of these crops was simulated by AquaCrop model, which was calibrated and validated by the observed field data from year 2012 to 2013. Then ArcGIS was applied for the pre/post processing of the AquaCrop to quantify the spatial distribution of water consumption and WUE in the regional scales, based on the spatial distribution of soil types, groundwater depth, agricultural management and cropping patterns.

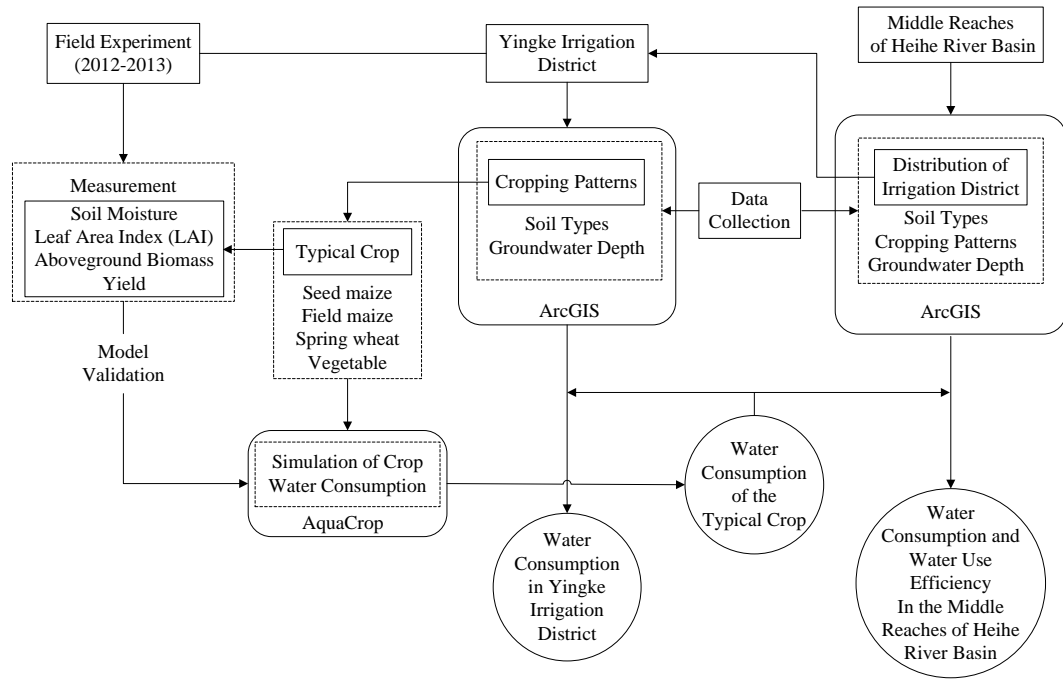


Fig. 1 Flow chart of the methodology

2.1 Study site

Heihe River Basin (37°-43°N, 97°-103°E) is located in northwest China and is a typical arid region. The middle reaches, covering an area of 13942 km² with 2379 km² of irrigated farmland, is to be studied in this research (Fig. 2). It has a temperate climate with the mean annual temperature varying from 0 °C to 5 °C, annual average precipitation of 129.6 mm and annual potential evaporation of 1400 mm. Soil moisture stresses are therefore common without irrigation. Typical crops in this region include the main food crops, i.e., field maize and spring wheat, the main cash food, i.e., seed maize, and some vegetables, e.g., cabbage. Due to the limited precipitation in the area, irrigation is required during the entire crop growing season (from April to October), with water diverted from either the Heihe River or pumped from the aquifer.

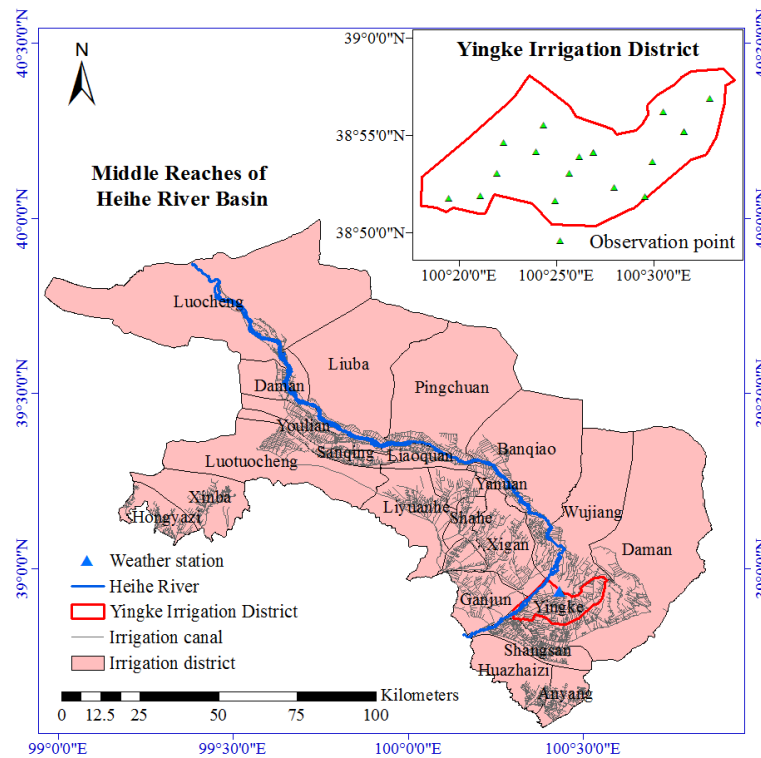


Fig. 2 Geographic location of the study area and distribution of the sampling points

2.2 Field experiment and data collection

2.2.1 Field experiment

The field observation was carried out in the farmland of field maize, seed maize and spring wheat in Yingke Irrigation District, which is one of the 17 main irrigation districts in Heihe middle reaches (Fig. 2) during the year 2012-2013 (Jiang et al. 2015). Leaf area index (LAI), and above ground biomass were recorded at intervals of about 10 days during the crop growing period. Soil moisture was also sampled at 20 cm intervals down to the 140 cm below ground surface using the gravimetric sampling method, every 10 days during the growing period, with three replicates (see Fig. 2 for the location of the observation points). Irrigation was applied according to the schedule

159 in Table 1. Soil moisture at field capacity and soil bulk density were also observed at the
160 same locations. According to the sampled soil texture in the irrigation district, the soil
161 types along the soil profile were identified into four types (Table 2).

Table 1 The irrigation schedule for different crops in 2012 and 2013

Crop		First	Second	Third	Fourth	Fifth	Sixth
Seed maize	Date	May 26,2012	Jun 22, 2012	Jul 21, 2012	Aug 13, 2012		
	Depth (mm)	160	230	230	230		
	Date	Jun 7,2013	Jun 28, 2013	Jul 29, 2013	Aug 22, 2013		
	Depth (mm)	300	120	200	200		
Field maize	Date	May 22,2012	Jun 22, 2012	Jul 22, 2012	Aug 22, 2012		
	Depth (mm)	200	200	200	200		
	Date	Jun 6,2013	Jun 1, 2013	Jun 28, 2013	Aug 24, 2013		
	Depth (mm)	165	165	150	150		
Spring wheat	Date	Apr 27,2013	May 25,2013	Jun 22,2013			
	Depth (mm)	165	165	150			
Cabbage	Date	Mar 20,2013	Apr 24,2013	May 19,2013	Jun 15,2013	Jul 11,2013	Aug 4, 2013
	Depth (mm)	100	100	90	90	85	85

Table 2 The main soil types along the soil profile

Soil type	Soil texture		Number of sample sites	Wilting point (%)		Field capacity (%)	
	0-80cm	80-140cm		0-80cm	80-140cm	0-80cm	80-140cm
T1	silt loam	silt loam	10	19	19	33	33
T2	silt loam	sandy loam	4	19	13	33	26
T3	silt loam	loam	9	19	15	33	29
T4	loam	loam	6	15	15	29	29

2.2.2 Data collection

Meteorological data including precipitation, relative humidity, hours of bright sunshine, average temperature, minimum air temperature, maximum air temperature and wind speed for Zhangye weather station (38°56'E, 100°26'N, 1482.7m) were obtained from the China Meteorological Data Sharing Service System (<http://cdc.nmic.cn/home.do>).

This weather station is the closest to the study area; consequently its measurements were taken as representative of the entire area. The weather data are required for ET calculation in AquaCrop. Digital elevation model (DEM) with a resolution of 1 km, land-use map and the soil texture map were all obtained from the Remote Sensing Laboratory of Cold and Arid Regions Environmental and Engineering Research Institute, China Academy of Sciences (Li et al. 2011).

Cropping patterns in Yingke Irrigation District (see Fig. 3) were obtained by field examination and Google map (Jiang et al. 2015). Fig. 3 showed that seed maize cultivation prevails in the southern part of the district, accounting for 44.48%, followed by the field maize (21.54%). Spring wheat was sparsely distributed, accounting for 7.14% of the area; consequently, interplant of field maize and spring wheat in mid/late June, before the maturity of spring wheat was also popular, accounting for 11.84%. Although this cultural practice required more irrigation water per year than planting only field maize or spring wheat, it nonetheless improved land use efficiency in the region. The rest of the cultivated lands were planted with the other vegetables, like cabbage.

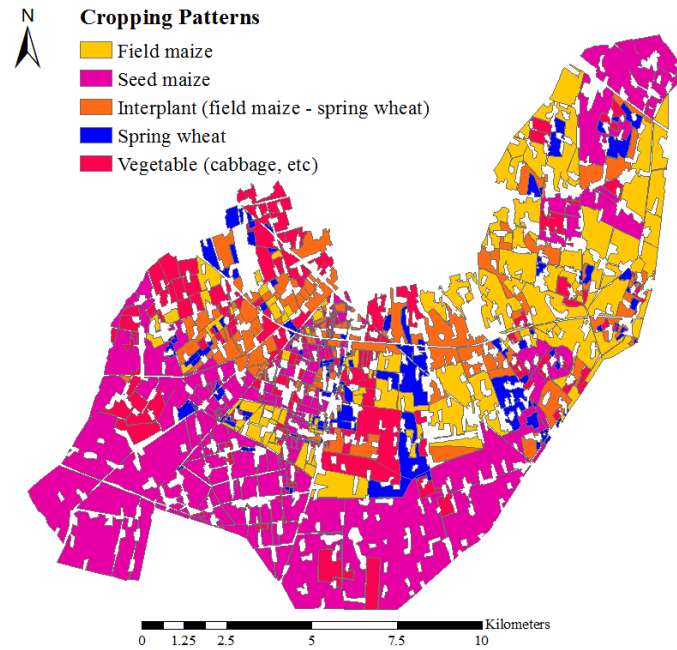


Fig. 3 Cropping patterns in Yingke Irrigation District

As to the whole irrigation districts in the middle reaches, there were no detailed cropping patterns available. We only obtained the ratios of planting area for the typical crops in each irrigation district from Zhangye Statistics Yearbook, as shown in Fig. 4 (a) Seed maize was the main crop in most districts, although some have the spring wheat and vegetable as their main crops. The ratios of different soil types in 0-140cm soil depth (T1 to T4) were converted from the soil texture map of 1:1000000 resolution and shown in Fig. 4 (b).

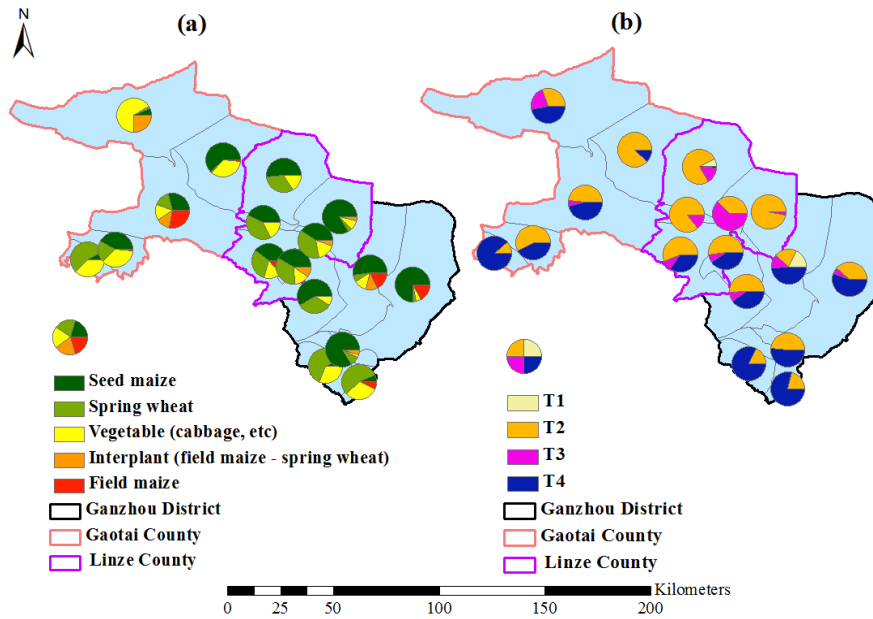


Fig. 4 Ratios of planting area for the typical crops (a) and ratios of different soil types (b) in each irrigation district in the middle reaches of Heihe River Basin

2.3 AquaCrop model description and related crop parameters

A full description of the theory and function of AquaCrop can be found in Steduto et al (2009); consequently only a brief summary of the model was provided here. The model simulated the soil water condition in the root zone using a water balance approach. The soil water condition together with the canopy cover information was then used to partition the FAO-PM ET to actual crop transpiration and soil evaporation. The canopy cover development was modelled using first order kinetics, albeit with facilities for accommodating stress (water, temperature, etc.) induced retardations. Then the biomass production was estimated from the actual crop transpiration using a normalized form of the water productivity (WP) parameter. Finally the crop yield was obtained from the biomass production using specified harvest index (HI).

The model inputs included meteorological conditions, initial values of the model

parameters, soil characteristics and management practices like irrigation schedules and water conservation measures such as mulching. Apart from HI and WP, AquaCrop has 20 parameters (see Table 3) for which conservative estimates were available in the User Manual for most commonly cultivated crops; these may generally be used without any further calibration (Vanuytrecht et al. 2014). For crops not covered in the manual and/or for deficit irrigation situations, calibration using field data was recommended.

The simulation depth of soil root zone was 1.40 m, which was enough for the root development. The groundwater table in the region was low (Jiang et al. 2015) and therefore capillary rise was unlikely to be significant and was therefore neglected. For the soil bottom boundary, the quantity of deep percolation was automatically calculated inside the model. The initial soil water condition was based on the observed results of soil samples.

The simulation outputs included the evolution of soil water depletion in the root zone, the development of the green canopy cover, and the daily transpiration; the soil water balance in a given period; the accumulation of biomass and the final yield. These were used to estimate the crop water use efficiency (WUE) as:

$$WUE = \frac{Y}{ET} \quad (1)$$

where Y is the crop yield ($\text{kg}\cdot\text{m}^{-2}$) and ET is the crop evapotranspiration, or the crop water consumption (mm).

2.4 Assessment of AquaCrop performance

To assess the performance of AquaCrop during calibration and validation, the root-mean-square error (RMSE), the Nash-Sutcliffe modeling efficiency (EF; Nash and Sutcliffe 1970) were computed as in Eqs. 2 & 3 respectively:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (P_i - O_i)^2} \quad (2)$$

$$\text{EF} = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (O_i - O_{ave})^2} \quad (3)$$

where N is the number of the evaluated points, P_i is the simulated value and O_i is the observation value, and O_{ave} is the average of the observation values, respectively.

The relative error in the simulated final yield was also evaluated using:

$$\text{RE}(\%) = 100 \frac{|Y_o - Y_p|}{Y_o} \quad (4)$$

where RE is the relative error (%), Y_o and Y_p are the observed and simulated final yields, respectively.

2.5 Methodology of extending the local AquaCrop simulation results to the regional scale

The crop water consumption and water productivity at regional scale was obtained by the loose coupling between AquaCrop and ArcGIS (see Fig. 1). ArcGIS software was used as a pre/post processor to generate and organize the input data as well as display the output data. For details, the spatial distribution of soil types, groundwater depths,

248 agricultural management and cropping patterns in the irrigation districts were grouped
249 into small units under the ArcGIS by its function of UNION, i.e., for each unit it had
250 the same soil type, groundwater depth range, irrigation schedule and the crop type.
251 Then, the data files in ArcGIS were transferred into Microsoft Excel. The Excel file
252 was used as the reference to generate AquaCrop input project files. Further, AquaCrop
253 model was run to simulate the crop growth and soil water balance for each unit, and the
254 outputs of AquaCrop were transferred back to the Excel file and then into ArcGIS by
255 the function of JOIN. Lastly, ArcGIS was used to present the spatial distributed
256 simulation results.

257 Note that in the middle reaches of Heihe River Basin, the cropping patterns were not
258 available as in Yingke Irrigation District. Therefore, the ratios of planting area of the
259 typical crops in each irrigation district were collected (see Fig. 4) and used as the area
260 weighting factors alternatively. The middle reaches was classified into several
261 irrigation districts, and for each irrigation district AquaCrop was run for each crop
262 type under the same soil type, groundwater depth and irrigation schedule. Then the
263 crop water consumption and water productivity in each district were obtained and
264 presented in ArcGIS by considering the area weighting factors of crop types.

3. Results and discussion

3.1 Model calibration and validation

3.1.1 Model calibration

AquaCrop was calibrated by the field observations including the evolution of averaged soil moisture in 0-140 cm depth, the above-ground biomass and the canopy cover of different crops. The calibrated parameters for seed maize, field maize and spring wheat are presented in Table 3.

Table 3 Calibrated parameters of AquaCrop model for each crops

Symbol	Description	Seed maize	Field Maize	Spring Wheat
CC ₀	Initial canopy size (%)	0.65	0.65	8.15
CGC	Canopy growth coefficient (%/day)	12.4	13.3	8.9
CDC	Canopy decline coefficient (%/day)	9.8	9.8	7.4
CC _x	Maximum canopy cover (%)	91	92	96
Z _x	Maximum effective rooting zone (m)	1.6	1.8	0.9
Z _n	Minimum effective rooting zone (m)	0.3	0.3	0.3
	Average expansion rate of the effective root zone (cm/day)	1.8	2.1	1.1
	Shape factor describing root zone expansion	1.3	1.3	1.5
Kcb _x	Crop coefficient	1.05	1.05	1.1
f _{sen}	Reduction coefficient	0.8	0.8	0.8
WP*	Water productivity normalized for ET ₀ and CO ₂ (g·m ⁻²)	33.7	33.7	17.5
	Percent WP* before yield formation (%)	66	71	100
HI ₀	Reference harvest index (%)	44	48	48
	Building up of HI (days)	39	39	38

The simulated and observed results of the averaged soil moisture in 0-140 cm depth were shown in Fig. 5. The simulated values were in accordance with the observations, with the simulated moisture content responding to water input through

irrigation/precipitation, followed by a gradual decrease due to the continuous evapotranspiration. At the end of the crop growth period, the simulation results showed a downward bias relative to the observation, especially in soil type T2. The reason may be that the model overestimates the root uptake and transpiration at the latter growth stages due to the inclusion of the non-transpiring dry leaves. This would result in the observed soil moisture content being higher than the simulated. When a good matching achieved between simulated and observed LAI (the former was converted from the direct output of AquaCrop, the canopy cover (Iqbal et al. 2010)), the actual root uptake should be lower than simulated value, because dry leaves were included in the observed LAI although without water consumption in the later stage.

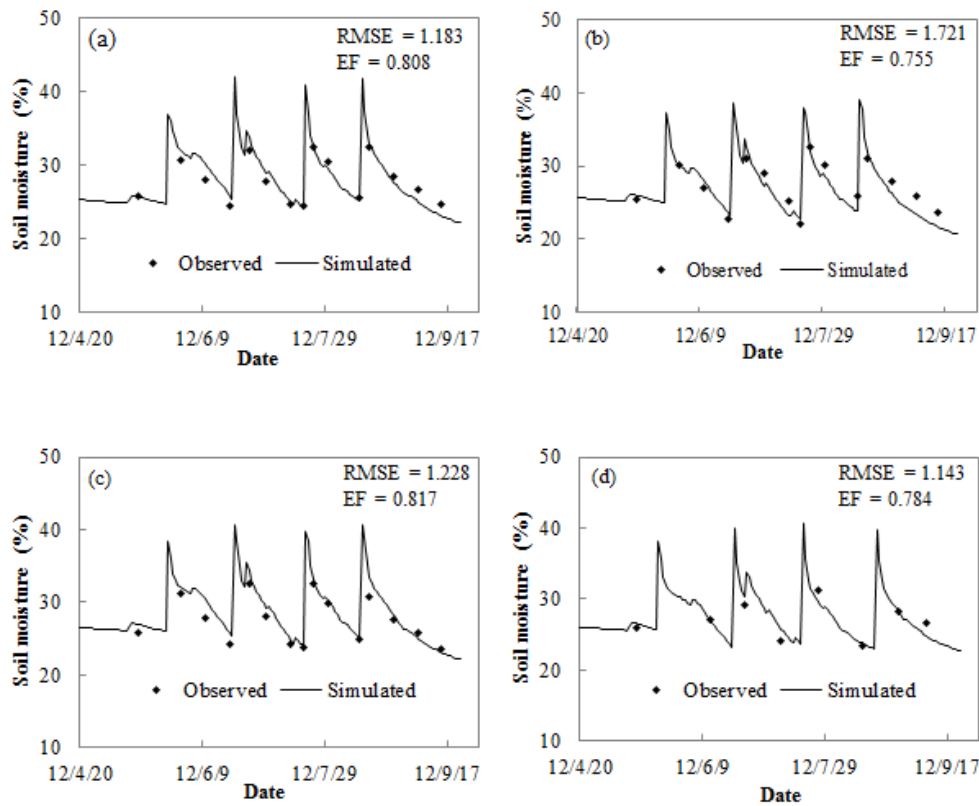
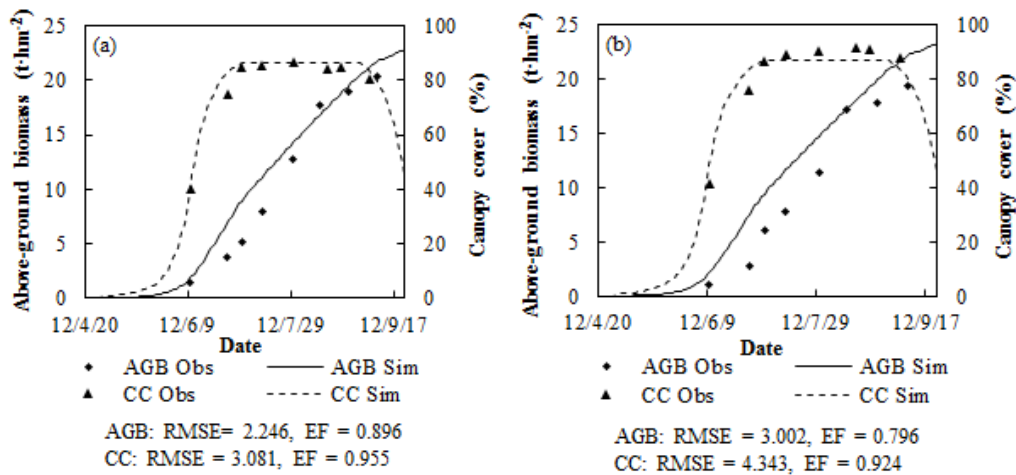


Fig. 5 Comparison of the averaged soil moisture in 0-140 cm depth between the simulated and measured data for seed maize with soil type (a) T1, (b) T2, (c) T3 and (d) T4 (for calibration in 2012)

Fig. 6 showed the results of canopy cover (CC) and the above ground biomass (AGB) of seed maize. The simulated CC was in good agreement with the observed values. CC of the seed maize expanded quickly from the seeding stage to the jointing stage and reached the plateau stage at heading stage, then decreased when senesced. Fig. 6 also showed that the simulation results of AGB were in reasonable agreement with the observed values, both increasing almost linearly during the growth period. Calibration results of yield for seed maize (Table 4) showed that the relative errors (RE) were all less than 5%, indicating that the model could simulate the soil water evolution and crop growth for seed maize well.



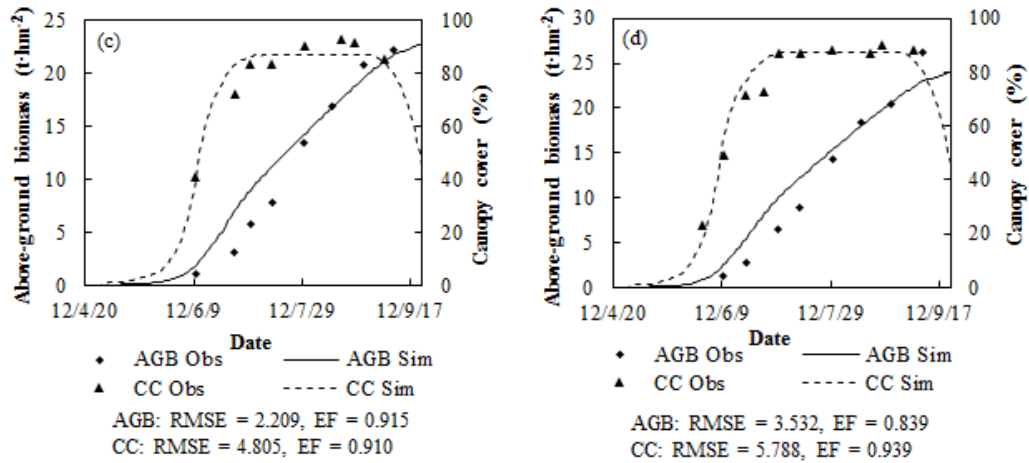


Fig. 6 Comparison of the above ground biomass and the canopy cover between the simulated and measured data for seed maize with soil type (a) T1, (b) T2, (c) T3 and (d) T4 (for calibration in 2012)

Table 4 Calibration and validation of yield for seed maize in different soil types

Soil type	Calibration			Validation		
	Observation (t·hm ⁻²)	Simulation (t·hm ⁻²)	RE (%)	Observation (t·hm ⁻²)	Simulation (t·hm ⁻²)	RE (%)
T1	10.322	10.052	2.62	8.33	9.208	10.54
T2	10.108	10.268	1.58	8.05	8.817	9.528
T3	10.111	10.036	0.742	8.47	8.762	3.447
T4	10.11	10.568	4.53	8.815	9.154	3.846

For field maize and spring wheat, the observed data in 2013 were used to calibrate the model, because their field observations were only conducted in 2013. Fig. 7 (a) revealed that CC of spring wheat was strongly sensitive to the soil moisture. There was a clear decrease in CC before the first two times of irrigation, mainly because the irrigation interval was a little longer for spring wheat and the resulting water stress in root zone had affected the crop growth. As to field maize, the crop growth was not affected because its irrigation was more frequent (although in small irrigation quota), and the reduction in the CC noticed for spring wheat had been noticeably absent for field maize. Therefore its CC was not decreased during the plateau stage, showing

similar trend like the seed maize.

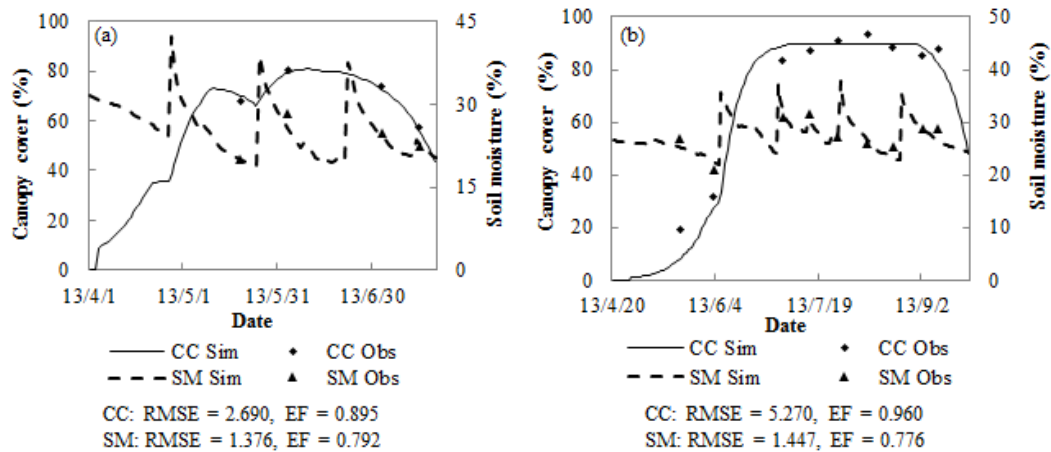


Fig. 7 Comparison between the simulation and observation of canopy cover and average soil moisture: (a) spring wheat in T1 soil type and (b) field maize in T4 soil type (for calibration in 2013)

The above work for three kinds of crops (as shown in Figs. 5-7) demonstrated that the simulation results agreed well with the observed data during calibration. RMSE of CC was between 3.08% and 5.79%. In terms of soil moisture, RMSE was from 1.14% to 1.72% and for AGB, RMSE ranged from 2.209 to 3.532 t·hm⁻². The model efficiency was all above 0.755 and some were near 0.97. Therefore AquaCrop model had a good ability to depict the fluctuation of soil moisture and the crop growth for typical farmland in this region.

3.1.2 Model validation

The model for seed maize was validated with experiment data in 2013 using calibrated parameters in Table 3, and the results were shown in Figs. 8-9. EF were all above 0.68 and some were nearly 0.97, indicating a good performance of this model and capable to be used for predicting the water consumption and water use efficiency of seed maize in the study area. The validation results of yield for seed maize (Table 4) showed the

relative errors (RE) of yield for seed maize in T1 and T2 were nearly 10%, which were larger than the calibration results. The reason was that there were diseases and insect pests in a certain period of 2013, which could reduce the actual crop yield. The AquaCrop model could not calculate the effects of the diseases and insect pests on the crop growth, leading to a higher simulation compared with the observation.

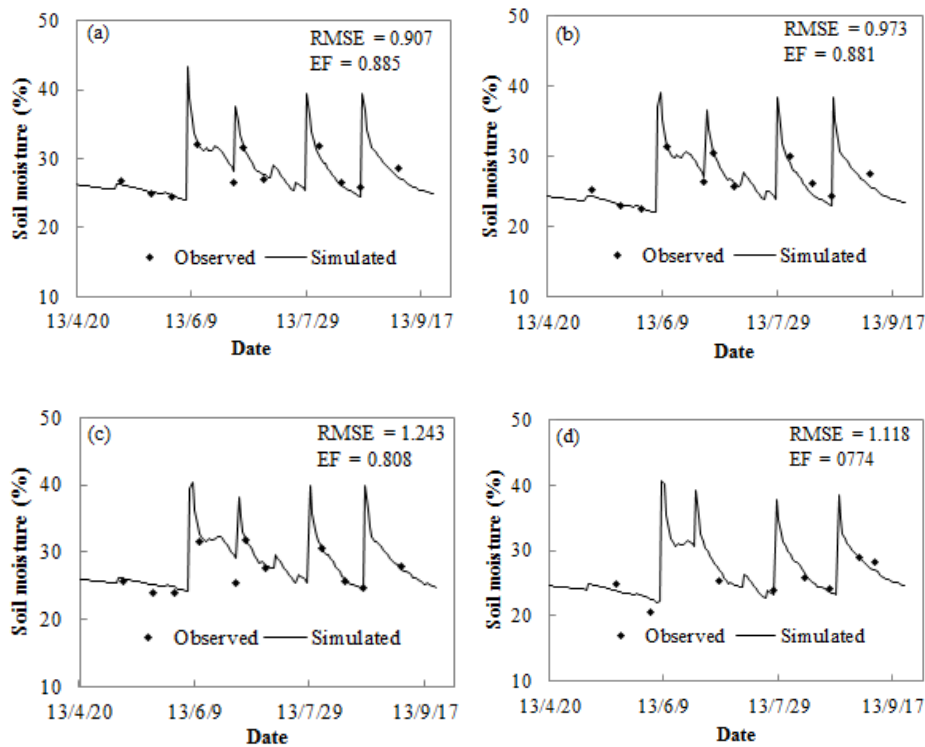


Fig. 8 Comparison of the averaged soil moisture in 0-140 cm depth between the simulated and measured data for seed maize with soil type (a) T1, (b) T2, (c) T3 and (d) T4 (for validation in 2013)

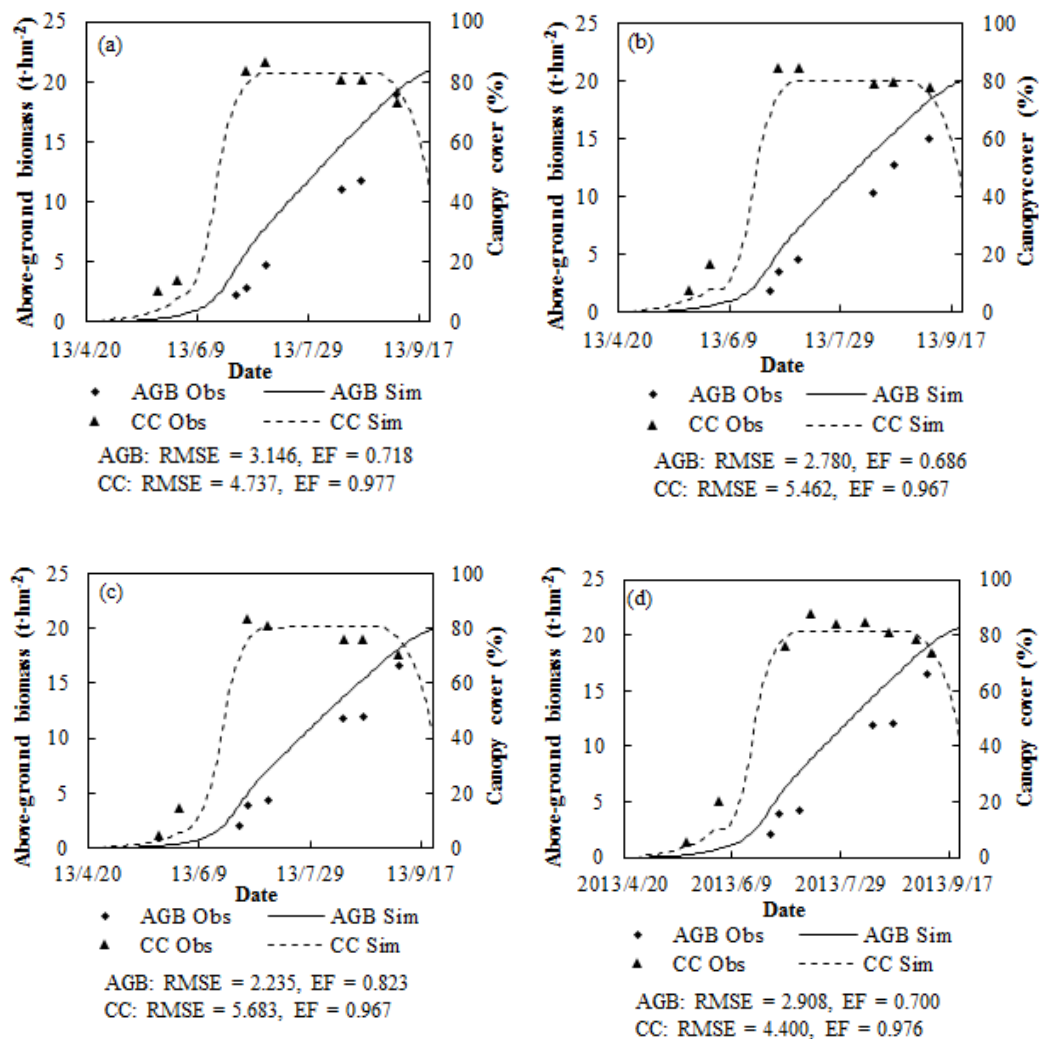


Fig. 9 Comparison of the above ground biomass and the canopy cover between the simulated and measured data for seed maize with soil type (a) T1, (b) T2, (c) T3 and (d) T4 (for validation in 2013)

For field maize and spring wheat, because there was only one year's field data that had been used for model calibration, no validation was performed for them.

3.2 Analysis of soil water balance and water consumption for typical crops in the middle reaches of Heihe River Basin

With the simulation results by AquaCrop, we analyzed the soil water balance and water consumption of the typical crops (seed maize, field maize and spring wheat) in the study area. Fig. 10 showed the evolution of the soil evaporation (E), transpiration (Tr),

evapotranspiration (ET) as simulated by AquaCrop, with the events of precipitation (P) and irrigation (I) for seed maize, field maize and spring wheat with a typical soil type (T1) in year 2012. Because E, Tr, ET had same trends in the growing stage in the different soil types in both years 2012 and 2013, the results of 2013 were not presented here.

For seed maize and field maize, due to the film mulching, a common agricultural practice in this region to preserve the soil temperature as well as to reduce soil evaporation, E was relatively small compared with Tr, especially in the mid and late stages, when canopy cover was large. ET evolution was generally in accordance with the development of canopy cover, although the climate condition was also an influencing factor. The maximum ET was about 7-8 mm/d for the four soil types, which was in accordance with previous research in this area (Zhou et al. 2012). In terms of spring wheat without film mulch, E was relatively larger than that of maize in all the growth stages. Besides, E and Tr can also be seen to increase following precipitation or irrigation. This demonstrated that the water consumption of spring wheat was highly influenced by the availability of soil water, indicating there was soil water stress in some growing stage.

The calculated ET in this study was within the range 496-600 mm for field maize and seed maize and 483-524 mm for spring wheat, which were similar to the results of similar studies. For examples, the estimated ET for irrigated maize in Heihe River Basin was 567 mm by a coupled model of HYDRUS and WOFOST (Li et al., 2012).

373 Zhao et al. (2010) used six methods to calculate ET of maize in the middle Heihe
374 River basin, with the results ranging from 552 to 778 mm. Some of these values are
375 higher than ours, mainly because they neglected the influence of soil water stress on
376 ET in their calculation methods. The simulation results of Jiang et al (2015) showed
377 that ET of maize was 545-691 mm and ET of spring wheat 417-439 mm by
378 SWAP-EPIC model.

379 The simulated ET were also in accordance with the value from previous research in
380 the other arid area of northwest China, For instance, ET in most area of Hetao
381 Irrigation District in Inner Mongolia was 500-650 mm (Yang et al. 2012) and ET of
382 spring wheat in Shiyang river basin was 350-591 mm (Tong et al. 2007).

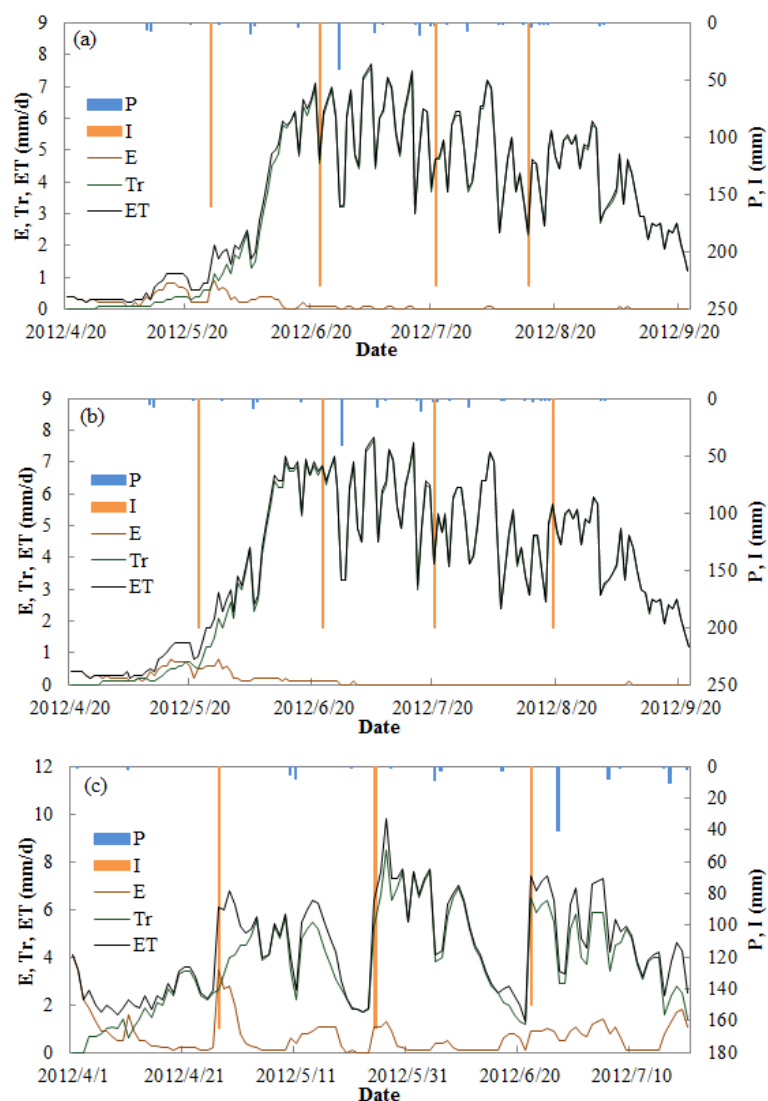


Fig. 10 The daily evaporation (E), transpiration (Tr), irrigation depth (I) and precipitation (P) for (a) seed maize, (b) field maize and (c) spring wheat in T1 soil type of the year 2012

Fig. 11 showed the total soil water balance, e.g., evaporation (E), transpiration (Tr), drainage (Dr), irrigation depth (I), precipitation (P), and the variation of water storage in root zone (St, positive indicates increase in soil water storage), under different soil types in years 2012 and 2013. Obviously the sums of I and P for different crops and soil types in these two years were all higher than ET, and the occurrence of drainage (Dr) as shown in the figure indicated that current irrigation practice in this region was not efficient. For seed maize and field maize, the water consumption in 2012 was higher

than that in 2013, with the mean ET 565.6 mm in 2012 and 504.0 mm in 2013 for seed maize and 586.95 mm in 2012, 562.18 mm in 2013 for field maize, because the first irrigation in 2013 was delayed, and crop experienced severe water stress which greatly influenced its growing condition and the subsequent water consumption. Unlike seed maize and field maize, there was little difference in ET for spring wheat in these two years (ET was 498.8 mm in 2012 and 499.3 mm in 2013). This was to be expected given that ET_0 was broadly similar in both years (665.7 mm in 2012 and 675.4 mm in 2013) and the irrigation scheduling was equally similar for spring wheat in 2012 and 2013.

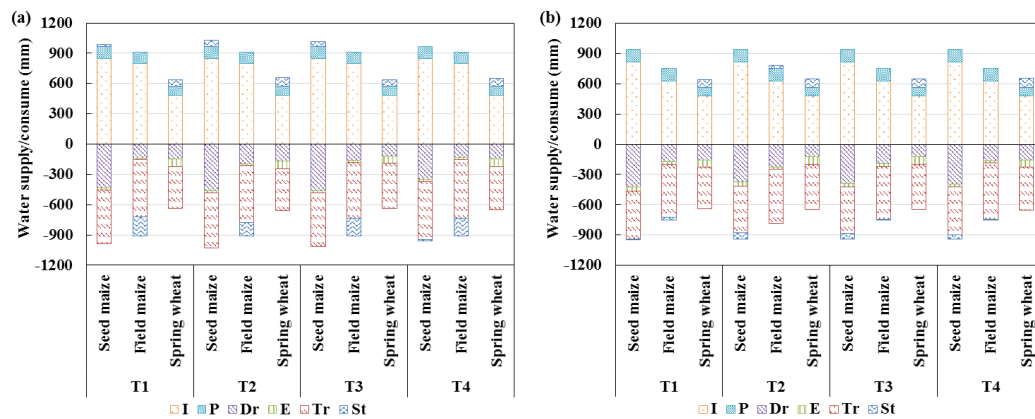


Fig. 11 Total evaporation (E), transpiration (Tr), drainage (Dr), irrigation depth (I), precipitation (P), and changes of water storage (St) for each crop type in different soil types of the year 2012 (a) and 2013 (b)

3.3 Analysis of water consumption in Yingke Irrigation District

AquaCrop was run for each unit in ArcGIS. As to the interplant, AquaCrop model could not simulate automatically the interplant crops. Therefore, the water consumption of interplant was calculated by an empirical method. Chai (2011) found that ET under interplant of wheat-field maize was 41.44%-47.15% higher than the average ET under

wheat and maize sole cropping systems based on field experiment in northwest China.

In the current study, the mid value was adopted, implying the water consumption of the interplant was 144% of the averaged water consumption of field maize and spring wheat. As to vegetable, the water consumption was simulated using the empirical parameters of cabbage in AquaCrop.

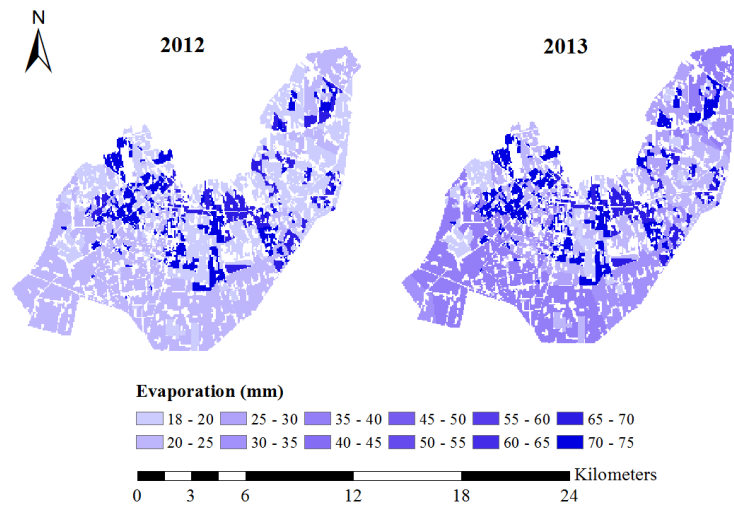


Fig. 12 Spatial variation of total annual evaporation in Yingke Irrigation District at the year 2012 and 2013

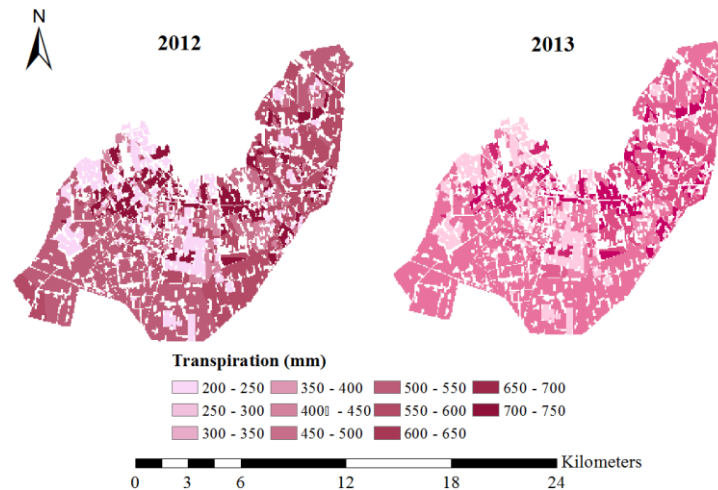


Fig. 13 Spatial variation of total annual transpiration in Yingke Irrigation District at the year 2012 and 2013

The simulated annual evaporation (E) and transpiration (Tr) in the Yingke Irrigation

District were shown in Figs. 12 and 13 and can be seen to be strongly linked to the cropping patterns. For example, higher E occurred in the field of spring wheat and interplant, mainly because they were not mulched. On the other hand, the highest Tr occurred in the fields of interplant, as a consequence of longer growing period and the enhanced Tr of the interplant as assumed. The overall E was smaller in 2012 than that in 2013, while Tr showed the opposite. As mentioned previously, this difference was due to the late first irrigation for maize in 2013, which decreased Tr.

Table 5 Water consumption of different crops under various soil types in year 2012 and 2013 (10^6m^3)

Soil types	Field maize		Seed maize		Spring wheat		Vegetable		Interplant	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
T1	2.04	1.94	12.68	11.69	1.24	1.24	1.84	1.83	3.71	3.61
T2	0.00	0.00	0.70	0.62	0.00	0.00	0.27	0.28	0.03	0.03
T3	5.12	4.89	8.84	7.88	0.83	0.81	1.03	1.01	2.17	2.13
T4	7.87	7.87	7.51	6.54	2.29	2.29	1.27	1.26	5.29	5.19
Total	15.03	14.70	29.73	26.72	4.36	4.34	4.40	4.38	11.21	10.96

The water consumption of different crops under various soil types in Yingke Irrigation District (with total planting area of 120.30 km^2) were listed in Table 5. It can be seen that seed maize had the highest water consumption, followed by field maize, and spring wheat had the lowest water consumption. Soil type T2 had the lowest water consumption because of its smallest distribution area. The simulated total water consumption in Yingke Irrigation District was $6.47 \times 10^7\text{ m}^3$ and $6.11 \times 10^7\text{ m}^3$, i.e., 538.09 mm and 507.91 mm in unit area in 2012 and 2013 respectively. These are similar to the 541.53 mm obtained by Wu et al. (2015) for ET in 2012 in Yingke Irrigation District.

3.4 Water consumption and productivity in the middle reaches of Heihe River Basin

In order to evaluate the water consumption and productivity in the whole middle reaches, we extended our study from this typical district to the whole middle reaches, including 17 main irrigation districts.

The water consumption in all the irrigation districts were shown in Fig. 14. Seed maize showed the largest water consumption in most of the irrigation districts, mainly because of its large planting area. Obviously water consumption decreased from east to west. In 2012, the total crop water consumption was $7.119 \times 10^8 \text{ m}^3$ in 2012 and $6.570 \times 10^8 \text{ m}^3$ in 2013. Compared with previous study on water consumption in the same area, our result was smaller than $10.87 \times 10^8 \text{ m}^3$ (Wu et al. 2015) and $11.06 \times 10^8 \text{ m}^3$ (Liu and Kotoda 1998). The reason mainly came from the difference in planting area. The planting area was $19.95 \times 10^8 \text{ m}^2$ in Liu and Kotoda (1998) and $23.88 \times 10^8 \text{ m}^2$ in Wu et al. (2015), which were both larger than $13.96 \times 10^8 \text{ m}^2$ in our study. Note that the data in Wu et al., (2015) and Liu and Kotoda (1998) came from remote sensing while ours from the Zhangye Statistics Yearbook. When comparing the averaged water consumption per unit area, those values were close to each other. In our research ET was 509.88 and 470.50 mm in 2012 and 2013 respectively, and it was 544.86 mm in Wu et al. (2015) and 463.15 mm in Liu and Kotoda (1998).

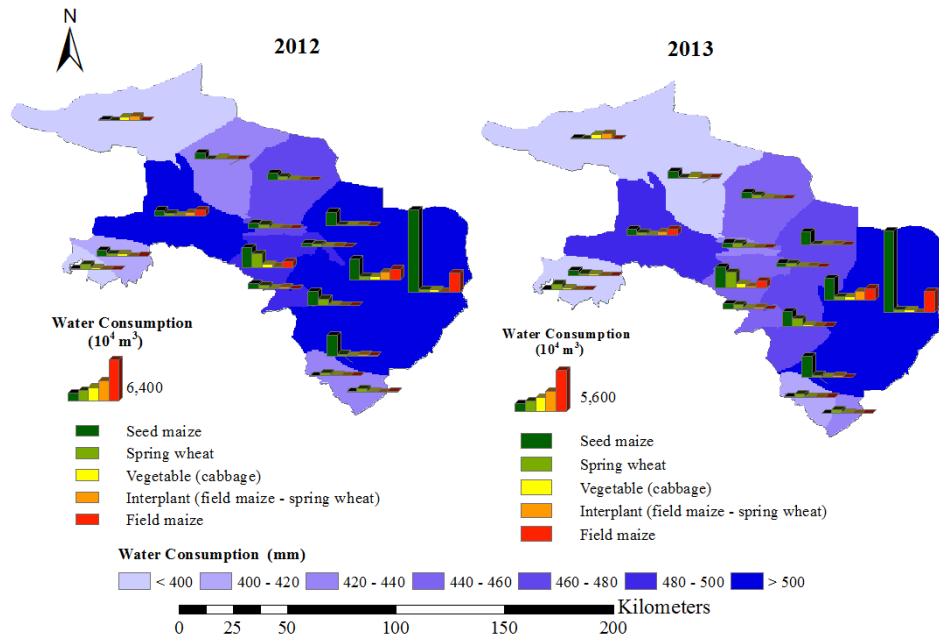


Fig. 14 Distribution of water consumption in middle reaches of Heihe River Basin

AquaCrop model could not automatically simulate the yield of interplant crops.

Therefore, the yield of interplant was calculated by an empirical method as suggested

by Li et al. (2008). Essentially, this involved using a nominal ratio of 1.30 for the yield

of intercropping of wheat and maize, relative to sowing winter wheat alone. Fig. 15

showed the calculated yield of the main crops and vegetables in each irrigation districts

in 2012 (similar results were also obtained in 2013, but not shown here because of the

limited space). The calculated total yields in middle reaches of Heihe River Basin were

1.30×10^9 kg in 2012 and 1.20×10^9 kg in 2013. Seed maize was the main cash crop,

whose yield accounted for 59.7% in 2012 and 56.5% in 2013 of the total yield,

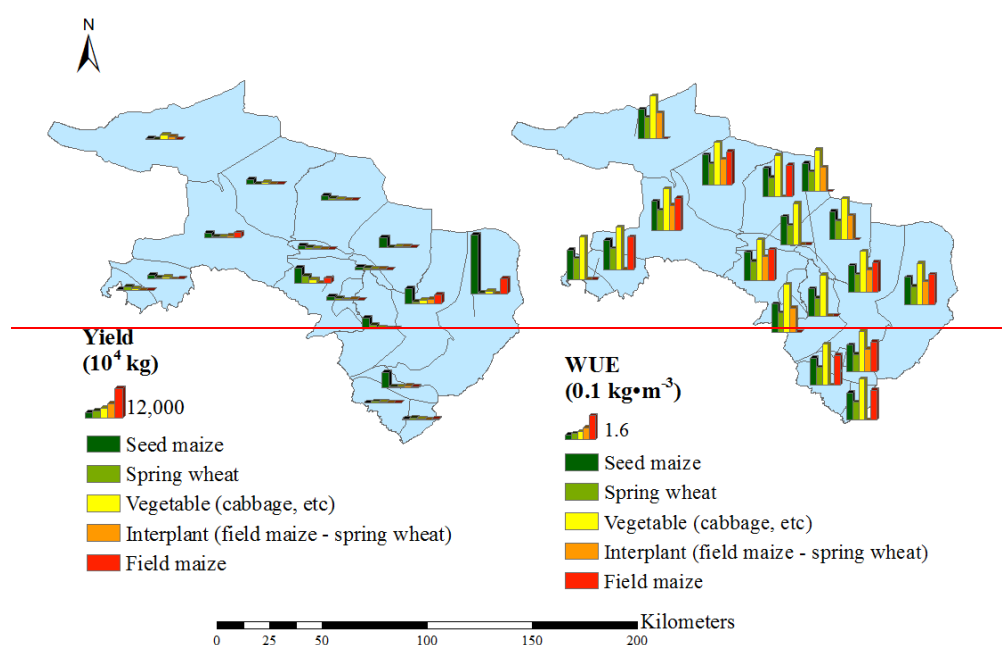
respectively. By averaging the yields of wheat and maize in 2012 and 2013 and in all

the 17 irrigation districts, the yield of wheat was $0.62 \text{ kg} \cdot \text{m}^{-2}$, and maize $1.08 \text{ kg} \cdot \text{m}^{-2}$.

They were in accordance with previous experimental data obtained by Yang et al.

474 (2011) in similar arid inland region, which were $0.56\text{-}0.72\text{ kg}\cdot\text{m}^{-2}$ for wheat and
 475 $0.78\text{-}1.12\text{ kg}\cdot\text{m}^{-2}$ for maize.

476 WUE in the entire basin could be calculated out (see Fig. 15), obviously vegetable had
 477 the highest WUE in all irrigation districts. WUE for seed maize (ranging $1.81\text{-}1.98$
 478 $\text{kg}\cdot\text{m}^{-3}$) and WUE for spring wheat (about $1.19\text{-}1.41\text{ kg}\cdot\text{m}^{-3}$) were close to the values by
 479 Jiang et al. (2015) for the same oasis area.



480

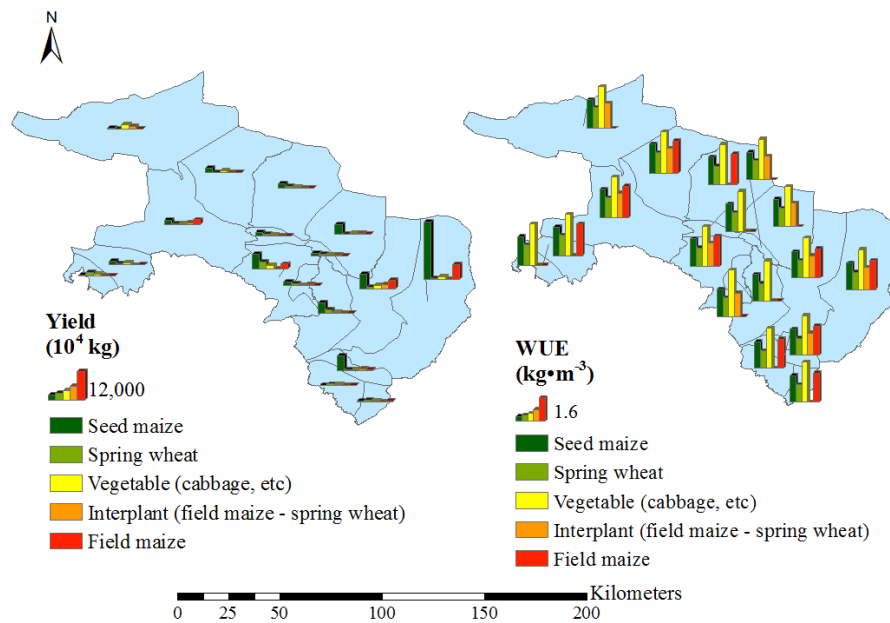


Fig. 15 Yield and WUE in the middle reaches of Heihe River Basin in 2012

3.5 Crop growth and water consumption under future possible climate change scenarios

Global climate change has caused extensive concern in recent years. Climate change may induce local variation in precipitation, temperature, etc., thus affecting the crop yield, crop water consumption and field water balance (Chen et al. 2010; Abrha et al. 2012). To investigate the possible influence of climate change on crop growth and water consumption, four future scenarios (S1 to S4) were assumed (Table 6) according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Nakicenovic 2000). Because the precipitation (125.1mm) in 2013 was close to the multi-year average value, the year 2013 was selected as the benchmark to predict the water consumption under future climate change. The input of climate data was modified according to the four scenarios while the other factors (e.g.,

soil data, crop parameters and other meteorological elements) remained the same as that of the year 2013.

Table 7 showed the relative changes of ET, WUE and yield. It demonstrated that higher temperature and CO₂ concentration would generally benefit the yield of maize (i.e., seed maize and field maize), but their ET would decrease, leading to a higher WUE, which was consistent with previous studies (see e.g. Guo et al. 2010). However, spring wheat responded differently to climate change. With higher temperature (S3), WUE for wheat decreased (largely due to the higher ET) but this trend was reversed with the increase of CO₂ concentration (S4). This indicated that the growth of spring wheat was very sensitive to CO₂ concentration. As noted by Conroy et al. (1994), the optimum temperature for photosynthesis would increase with the increase of CO₂ concentration; hence it caused the reversal in the yield and WUE for spring wheat when both the CO₂ and temperature increased.

Table 6 Scenarios of future climate (based on the average temperature of the year 1961 to 1990)

Year	Scenarios	CO ₂ (ppm)	Temperature
2030	Scenario 1 (S1)	395	+1.7°C
	Scenario 2 (S2)	429	+1.7°C
2050	Scenario 3 (S3)	395	+2.8°C
	Scenario 4 (S4)	478	+2.8°C

Note: S1 and S3 with only the increase of temperature; S2 and S4 with the increase of both temperature and CO₂ concentration.

Table 7 The relative increase of yield and WUE under climate change

Crop	Scenarios	ET	Yield	Relative increase of yield	WUE	Relative increase of WUE
		(mm)	(t·hm ⁻²)	(%)	(kg·m ⁻³)	(%)
Seed	Status quo	599.5	11.452		1.91	

maize	Scenario 1	605.2	11.885	3.78	1.96	2.62
	Scenario 2	588.3	11.843	3.41	2.01	5.24
	Scenario 3	615.7	11.905	3.96	1.93	1.05
	Scenario 4	594.3	12.088	5.55	2.03	6.28
Field maize	Status quo	622.4	12.964		2.08	
	Scenario 1	622.7	13.364	3.09	2.15	3.37
	Scenario 2	612.9	13.415	3.48	2.19	5.29
	Scenario 3	638.7	13.417	3.49	2.11	1.44
	Scenario 4	620	13.712	5.77	2.21	6.25
Spring wheat	Status quo	502.6	6.184		1.23	
	Scenario 1	501.3	6.366	2.94	1.27	3.25
	Scenario 2	497.3	6.702	8.38	1.35	9.76
	Scenario 3	503.6	6.16	-0.39	1.22	-0.81
	Scenario 4	498.5	7.047	13.96	1.41	14.63

4. Conclusions

Based on the field experiments and data collected in the middle reaches of Heihe River Basin, AquaCrop model was calibrated and validated for simulating the crop water consumption, soil water balance and crop yield for the typical crops (i.e., maize, wheat and vegetable). With the pre/post ~~proecessment~~ processing by ArcGIS, AquaCrop were further applied for calculating the spatial distribution of crop water consumption and WUE in a typical irrigation district and in the whole middle reaches. Good comparisons were seen between the observed and simulated soil water depletion in the root zone, canopy cover development and biomass accumulation. These indicated that AquaCrop could reasonably simulate the crop growth, water consumption and soil water balance in this area. The regional distribution of simulated crop water consumption and WUE showed that the spatial distribution of crop water consumption was greatly influenced by the cropping patterns, with higher evaporation occurred in

the field of spring wheat and interplant, and higher transpiration occurred in the field of interplant. In the middle reaches of Heihe River Basin, seed maize had the largest yield, while vegetable had the highest WUE according to the simulation results in 2012 and 2013. The responses of crop growth and water consumption under future possible climate change scenarios were also simulated. Results generally showed higher yield and WUE with future possible climate changes, although spring wheat is more sensitive to the CO₂ concentration and heat stress, and may likely show different trend with elevated temperature and lower CO₂ concentration in the future.

It must be noted that this work was conducted with limited available data. In order to simulate more accurately the regional crop water consumption and WUE, more detailed investigation on the soil texture/structure, the regional distribution of crop types, irrigation scheduling is required. Besides, no lateral groundwater flow was considered in our regional simulation. Local area with large groundwater table fluctuation may induce substantial later flow and influence the water exchange between saturated/unsaturated zones, which should not be overlooked in future studies.

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